Chapter 9: Test Structures

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As previously mentioned, there is a serious debate within the MEMS community about the materials properties of thin films. Accurate knowledge of these properties is critical for assessing the long-term reliability of MEMS devices. In order to measure thin film properties and make these basic assessments, test structures are needed. Test structures are, in their simplest sense, sensors. Instead of sensing external forces they sense the environment they are exposed to. Most fabrication facilities utilize test structures on their production line to assess the quality of their process.

In order to ensure reliable operation, test structures that characterize both the process and materials used to manufacture devices must be made concurrently. It is the analysis of these test structures that will enable systems engineers to incorporate MEMS into their designs with a high degree of confidence in their reliability. This chapter describes some of the basic test structures used and their implications.

I. Technology Characterization Vehicle

A technology characterization vehicle, or TCV, is a structure that is used to evaluate the effects of specific failure mechanisms on a technology. Typically the devices used in TCVs will be derived from a standard library of device elements. This library might include cantilever beams, membranes, and other structures that are used commonly in MEMS technology.

Technology characterization vehicles will be subjected to a given test in order to predict failure from particular failure mechanisms. These structures should be used to determine an estimate of the mean-time-to-failure and failure probability models. The use of these devices is a critical part of the qualification process, as they provide a wealth of knowledge about the reliability of structures. TCVs should be packaged and handled exactly the same as other MEMS so that the information that they provide is as accurate as possible.

II. Standard Evaluation Devices

A standard evaluation device, or SED, is similar to a TCV except that an SED is not constructed out of typical design elements, but is instead constructed out of actual sensor and actuator structures. Usually the SED is a less complicated version of a completed device and provides reliability information about the performance of devices instead of structures. In a good quality control process, the parameters measured in different SEDs will be compared across wafers and lots to determine reliability characteristics of production runs. As in TCVs, SEDs should be treated in the same fashion as a fully functional device.

III. Parametric Monitors

Parametric Monitors, or PMs, are used as a method to measure the properties of the materials used in MEMS devices. Unlike TCVs and SEDs, a PM is designed solely as a test structure and is not just a part of a pre-existing design. While PMs have long been used in the electronics industry, their use for the measurement of the mechanical properties of materials is relatively new. For this reason, several basic structures will be described in the following section to illustrate the recent developments in this field.

As with other test structures, the data collected from PMs will be compared across production runs to examine the effects of processing conditions on material properties.

A. Beam Stubs

Many processes include the dimensions of thin film layers in their design specifications. A typical surface micromachining process might state that the poly 2 layer is 3 microns thick and that the oxide layers are all 2 microns thick. In order to verify the actual dimensions of the process run, beam stubs are employed. Beam stubs are simply short cantilever beams with open cross sections. Usually an engineer will examine these beams to guarantee that the internal composition of each process is what it was supposed to be. This is a simple procedure performed with a scanning electron microscope. Measuring the internal composition of beams stubs allows the determination of the moment of inertia and mass of structural beams.

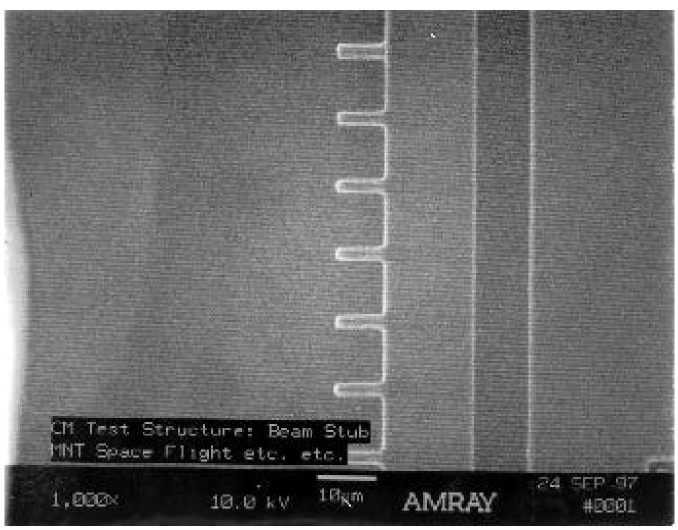

Figure 9-1: A row of beam stubs. (from JPL)

B. Elastic Measurements

In order to optimize MEMS designs, the elastic properties of materials must be known. To make these measurements, several established techniques are used.

i) Bending Beam Method

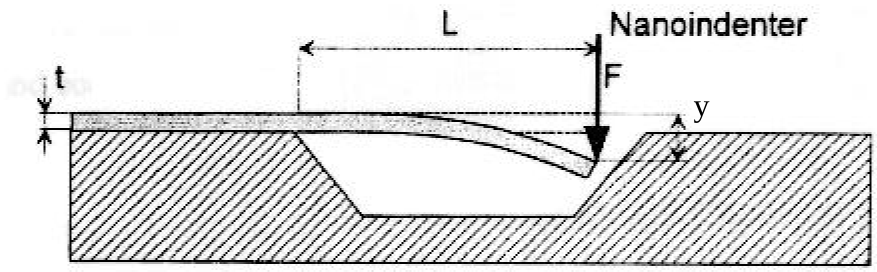

Figure 9-2: Bending beam method. (from [126])

One method of measuring Young's modulus employs static loading of a cantilever beam. A nanoindenter is applied to one end of a beam and the force-displacement curve is measured. For a small deflection, Young's modulus can be obtained as[1]:

$$E = \frac{FL^3}{3yI} \tag{9-1}$$

where the dimensions are labeled in Figure 9-2. This method can also be used to measure the modulus of thin films on multilayered beams that have residual stress. The modulus of a thin film, E_f, can be related to the modulus of a structural material, E_s, for $t_f << t_s$:

$$E_f = \frac{1}{3}\left(\frac{t_s}{t_f}\right)\left(\frac{\Delta F}{F_0}\right)E_s \tag{9-2}$$

where:

F_0 = the force required to displace an uncoated beam d_0

ΔF = (the force required to displace a coated beam d_0) – F_0

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[1] A common alternative to this equation attempts to linearize the nonlinear factors in Equations (9-1) and (9-2). This method defines $E' = E/1-v^2$.[40]

This method is only effective for films with little to no residual stress. Furthermore, this technique, due to the cubic powers in Equation 9-1, is critically limited by the ability to accurately measure the dimensions of the beam.[126]

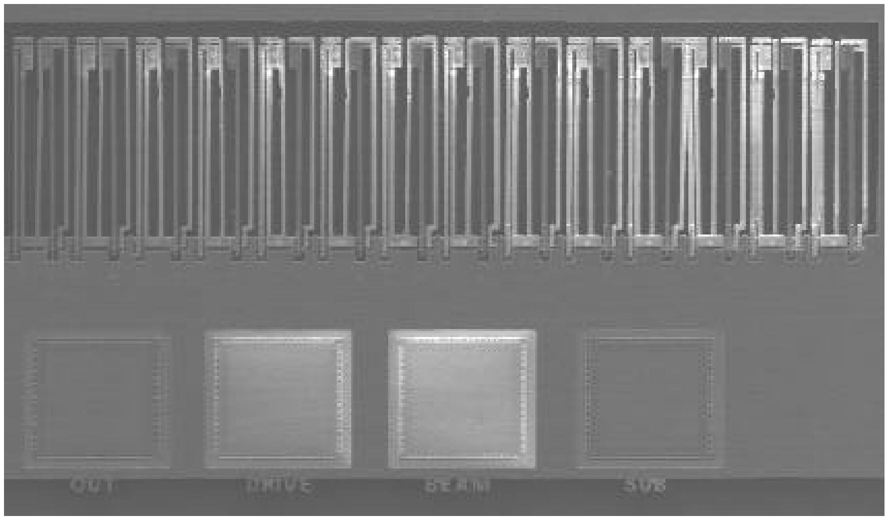

Figure 9-3: Resonant beam array.

ii) Resonant Beam Structures

Resonant beams are structures designed to measure the stiffness of beams. Equation 6-8 described the resonant frequency of beams as:

$$w_0 = \sqrt{\frac{k}{m_{eff}}} \tag{6-8}$$

This equation shows that measuring ω_o and m_{eff} will give k. The dimensions of a beam can be measured using beam stubs. Multiplying these dimensions by published densities will determine the mass of these beams. The resonant frequency is usually measured either internally through parallel plate capacitors or externally by a laser vibrometer. Once these values have been measured, it is fairly simple to extract Young's modulus from the equations in Section 6-I. For a cantilever beam, Young's modulus is:

$$E = \frac{.92 w_o^2 m l^3}{a^3 b} \tag{9-3}$$

Another structure used to measure Young's modulus is a lateral comb drive resonator. This structure is useful for measuring the properties of LPCVD deposited polysilicon and has the desirable property that dampening at atmospheric pressure is extremely low.

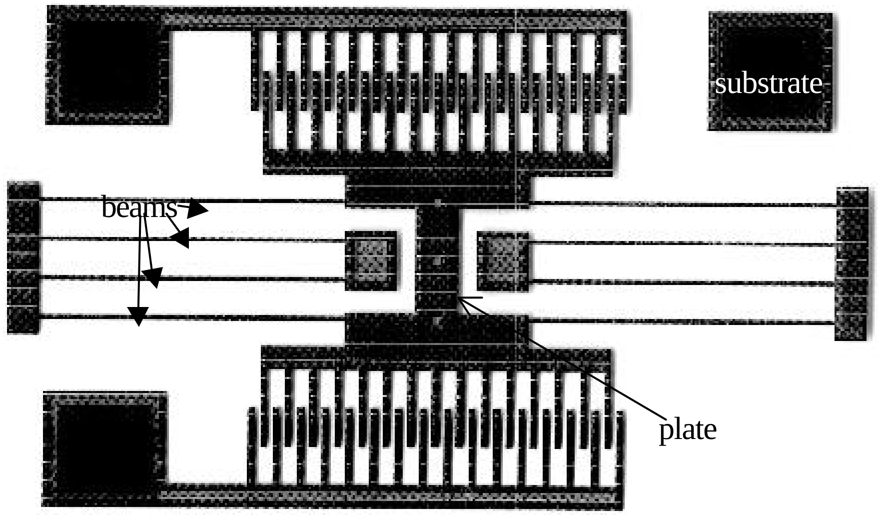

Figure 9-4: Layout of comb-drive resonator.

For these structures, the resonant frequency is related to Young's modulus by: [24]

$$w_0 = \sqrt{\frac{2Eba^3}{L^3\left(M_p + .03714M\right)}} \tag{9-4}$$

where Mp and M are the respective masses of the plate and the beams.

Typically resonant beams are used to measure Young's modulus and to compare it against published values. Since the values of Young's modulus differ across process lines, it is useful to have made measurements on the same wafer as actual devices. One drawback of this device is that plate mass is difficult to measure accurately.

C. Stress/Strain Gauges

With residual stress having been established as a serious reliability concern, there has been a serious push for devices capable of measuring residual stress in MEMS. There are a number of methods to measure internal stress, all of which have varying degrees of usefulness and precision. This section will examine some of the more common methods for measuring stress.

i) Bent Beam Strain Sensors

Bent beam strain sensors are common devices used in measuring internal strain in a device. Initially described by Gianchandani and Najafi in 1996, these devices are popular strain gages due to the fact that they can measure both compressive and tensile stresses. Shown in

Figure 9-5, these structures are constructed of two built-in beams connected to cantilever beams.

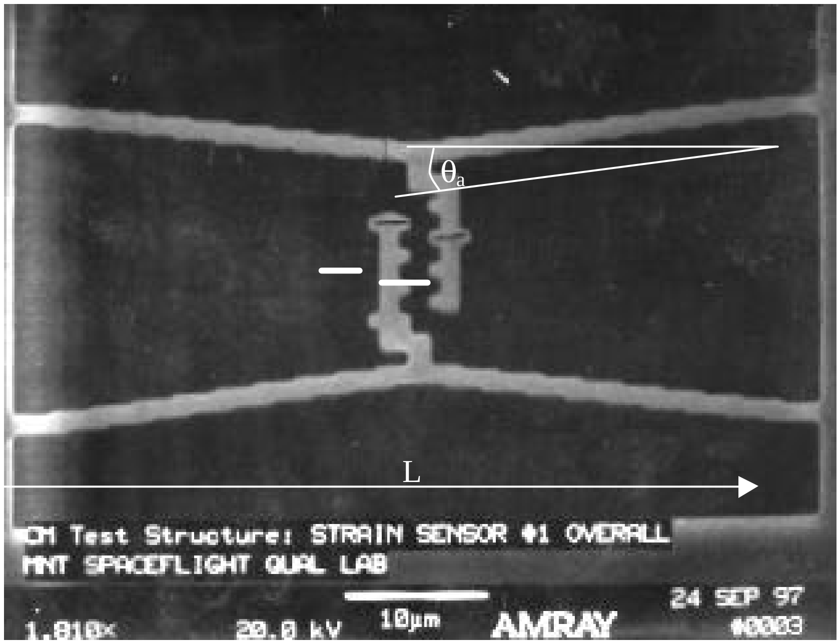

Figure 9-5: Stress/strain gauge. The two marked stubs were aligned prior to release.

The cantilevers are covered with a vernier scale. Upon release from the substrate, these structures will shift position due to internal stresses. By measuring the deflection of the teeth of the vernier, it is possible to extract stress measurements. This can be done with a computer through finite element analysis, but an excellent analytical approximation of this model is given by:[30]

$$s_{\text{int}} = \frac{E}{L}\left(\Delta L' + \frac{FL}{Eab}\right) \qquad (9\text{-}5)$$

where

F = load applied to beam by internal stress

L = distance indicated in Figure 9-5

L' = the difference between the actual length of the beam and L, which is equal to

$$\frac{L'}{2} = -\frac{1}{2}\int_0^{L/2}\left(\frac{\partial y}{\partial x}\right)^2 dx \qquad (9\text{-}6a)$$

When solved, L' becomes:

$$L' = \frac{(\tan(q_a))^2}{4k}\left[2H + kL - kLH^2 + \sinh(kL) - 2H\cosh(kL) + H^2\cosh(kL)\right] \text{in} \tag{9-6b}$$

tension and

$$L' = \frac{(\tan(q_a))^2}{4k}\left[2G + kL + kLG^2 + \sin(kL) - 2G\cos(kL) - G^2\sin(kL)\right] \tag{9-6c}$$

in compression

where

G = tan(kL/4)

H = tanh(kL/4)

k = $\sqrt{\frac{F}{EI}}$

The displacement y is related to k, and thus L' by the relationship

$$y_{Tension} = 2\frac{\tan(q_a)}{k}\tanh\left(\frac{kL}{4}\right) \tag{9-7}$$

$$y_{Compression} = 2\frac{\tan(q_a)}{k}\tan\left(\frac{kL}{4}\right) \tag{9-8}$$

These structures are limited in resolution by the minimum feature size of a technology. While these limitations are usually small, they could be a serious problem on some larger technologies, such as LIGA. Out-of-plane displacements caused by stress gradients and non-uniform beam thickness can inhibit device sensitivity. Ultimately these devices will have difficulty being accurate below 10 MPa.[30]

ii) Cantilever Beams

Cantilever beams are commonly used as a simple way to measure internal stress. Since most technologies utilize cantilever beams, it is a relatively simple step to place extra cantilever beams onto a device for stress measurement. One method uses cantilever beam deflection to measure stress. Since most stresses on these devices causes non-planar displacement, a system that can measure z-axis deflection can measure stress. With a multitude of laser interferometery systems now available to measure surface topology, these measurements are easy to make both quickly and accurately.

Since internal stress is rarely uniform, but is instead a function of material thickness, many researchers are interested in the stress gradient within a material. The stress gradient is calculated by looking at the change in stress over the change over film thickness. For a cantilever beam, the stress gradient can be analytically approximated by:

$$\frac{ds}{dt} = \frac{2yE}{(1-n)l^2} \tag{9-9}$$

where

y = non-planar deflection of the cantilever tip

t = thickness of the film

l = length of the cantilever

While this equation assumes a linearly varying stress field, this is not an unrealistic assumption. Although this equation does not take into account many of the irregularities considered in a finite element analysis, it does offer a good order of magnitude calculation for the stress field within thin films.

iii) Buckling Beam Structures

Many test structures take advantage of buckling behavior in beams to measure stresses. The stress needed to buckle a doubly clamped beam is defined as:

$$s_b = -\frac{p^2 h^2 E}{3L^2} \tag{9-10}$$

where

h = beam thickness

L = beam length

As such, for structural beams, buckling is a function of stress levels. Designers have used this fact in creating arrays of these beams. Each beam in the array has different dimensions, with a corresponding buckling stress. By examining the beams after release it is possible to measure stress by observing the beam with the largest σ_b that buckled. This technique is a very accurate way of measuring compressive stresses in beams. With longer beams having a σ_b<1 MPa, these arrays can be quite sensitive.

For tensile stresses, another set of test structures called Guckel Rings, has been developed to utilize buckling in measuring stresses. Guckel Rings are also used in arrays and the critical buckling load is defined by:[130,138]

$$\sigma_b = \frac{\pi^2 h^2 E}{12 g(R) R^2} \tag{9-11}$$

where

R = ring radius

g(R) = a function of inner and outer ring radius ≤ 0.918

iv) Substrate Analysis

One method to measure stress in thin films does not use actual test structures as they are commonly known. Instead this technique uses substrate deformation to measure stress. This is done by measuring the radius of curvature of the substrate before and after deposition of a thin film. Then the Stoney equation can relate these measurements to the residual stress:[139, 140]

$$\sigma_r = \frac{E t_s^2}{6(1-\nu)t}\left(\frac{1}{R_o} - \frac{1}{R_f}\right) \tag{9-12}$$

where

R_o, R_f = initial and final radii

t = thin film thickness

t_s = wafer thickness

This method provides good residual stress measurements down to about 10 MPa. Below this level, boundary conditions and gravity affect measurement accuracy. The major limitation of this method is that it does not provide direct measurement of stresses in finished devices.

D. Undercut Squares

Another area of concern in MEMS is the width of an isotropic undercut etch. These etches are critical to releasing structures, and many researchers are interested in determining how thick of a structure can be undercut. The simplest way to make a test structure to measure this is to create an array of squares. The squares vary in size from a dimension that clearly can be undercut to a dimension that clearly cannot be undercut. After release, the structures that have been fully undercut will be separated from the substrate, while the structures that have not will still be intact.

IV. Fracture Specimens

The most common method used to measure fracture strength is to place a static load on a cantilever beam. This technique is similar to static elastic property measurements, with larger loads and deflections.

Another method reported by Tsuchiya et al.[127] involves a tensile tester for thin films that holds samples electrostatically. This method requires that the tester is placed into a SEM to measure displacement, as shown in Figure 9-6.

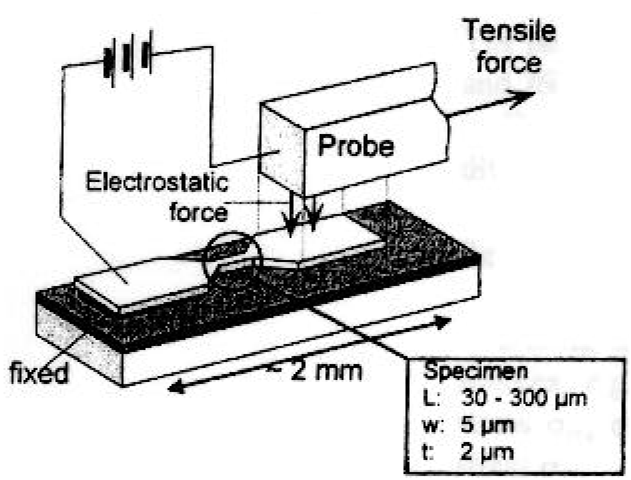

Figure 9-6: Tensile tester reported by Tsuchiya et al. (from [127])

A less complicated method described by Greek et al. is to use a probe tip connected to a thin beam. By applying a force to the probe, it is possible to measure fracture stress.[128,129]

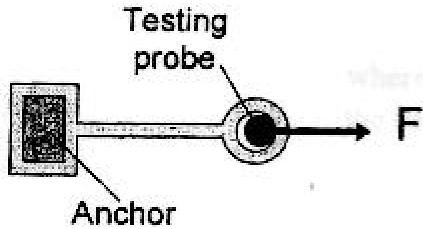

Figure 9-7: Tensile tester reported by Greek et al. (from [128])

A. Thermal Properties Measurements

The thermal properties of MEMS are important for a number of applications. It is important to accurately know the linear expansion coefficient and the thermal conductivity for certain devices. There are several methods to do this.

i) Cantilever Beam Method

A cantilever beam can be used to measure the linear coefficient of expansion. By measuring the change in curvature, $\Delta(dy/dx)$, for a given change in temperature, it is possible to determine the linear coefficient of expansion of a thin film material, α_f:[131]

$$\Delta \frac{dy}{dx}(\Delta T) = \frac{(a_f - a_s)}{C}\Delta T \tag{9-13}$$

where

α_s = the coefficient of expansion of the substrate (a well-known value)

$$C = \frac{E_s t_s^2}{6E_f t_f}\left(1 + \frac{t_f}{t_s} + 4\frac{E_f t_f}{E_s t_s}\right)$$

ii) Thin Film Heater

One popular method for measuring the thermal conductivity of a film employs a thin film heater attached to the free end of a cantilever beam. The temperature gradient between the heater and the fixed end of the cantilever can be determined via a row of thermocouples, as shown in Figure 9-8.[129,132,133]

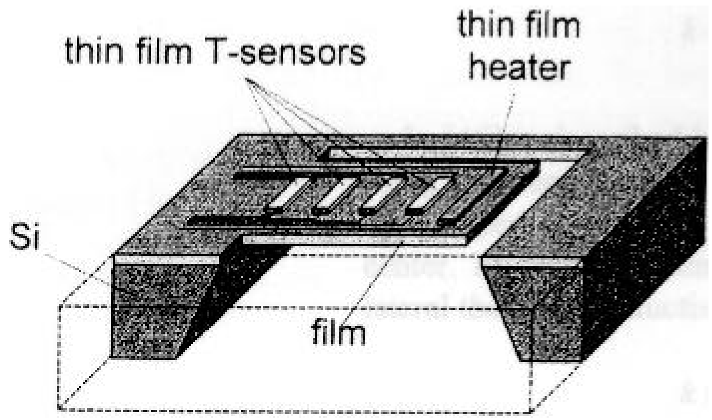

Figure 9-8: Layout of thin film heater with thermocouples. (from [129])

The thermal conductivity for one of these devices is calculated as:

$$k = \frac{P}{A\left(\frac{dT}{dx}\right)} \tag{9-14}$$

where

P = applied thermal power

A = the area normal to the heat flow

iii) Microbridge

Another method to measure thermal conductivity involves a microbridge. The bridge is doped less in the center so that it has a greater resistance. Then a current heats up the bridge and the I-V curve is measured to determine the thermal conductivity:[129, 134]

$$k(T_c) = \frac{I}{wt}\frac{dP}{dT_c} \tag{9-15}$$

where w, t, and T_c are defined in Figure 9-9.

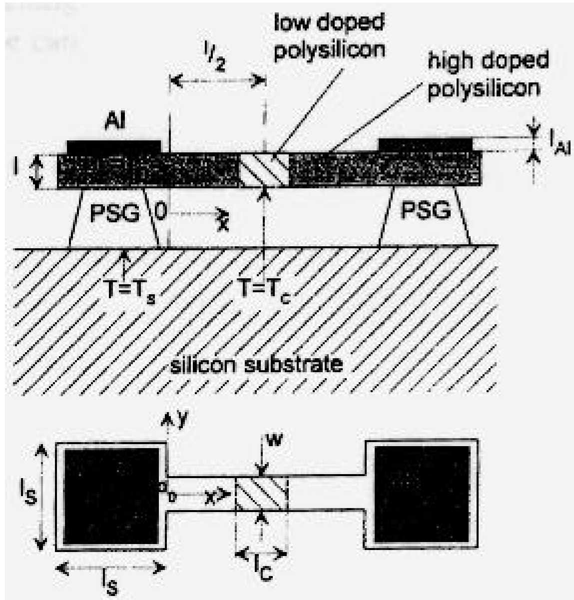

Figure 9-9: Layout of a microbridge. (from [129])

V. Additional Reading

E. Obermeier, "Mechanical and Thermophysical Properties of Thin Film Materials for MEMS: Techniques and Devices" *Materials Research Society Symposium Proceedings*, Vol. 444.